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14. ABSTRACT

As missions for Explosive Ordinance Disposal (EOD) units and Special Operations Forces (SOF) move closer into coastal and even "riverine" areas, there is an increased requirement for information on water clarity. This water clarity is important from the standpoint of detecting mines and minelike objects (MLO) on the bottom, in the water column, or attached to the hull of a vessel. It is also important for insersion of an EOD or SOF divers into harbors and hostile areas undetected for demining operations. In addition, as missions move at a more demanding pace, environmental intelligence is critical in determining when and where operations are most likely to be successful. Environmental information is now demended on the order of minutes to hours and not days to weeks. The reality of dealing with variable environmental conditions was no where more apparent than during OPERATION IRAQI FREEDON (OIF). During OIF there were several missions that relied on the timely delivery of water clarity information. Here we present how ocean color imagery was utilized to support EOD and SOF operations during OIF and how algorithms developed within one week were used for active operations. We also show the integration of current data into the products that allowed the warfighter to evaluate several key environmental factors.

15. SUBJECT TERMS

Operation Iraqi Freedom, water clarity, diver visibility, ocean color

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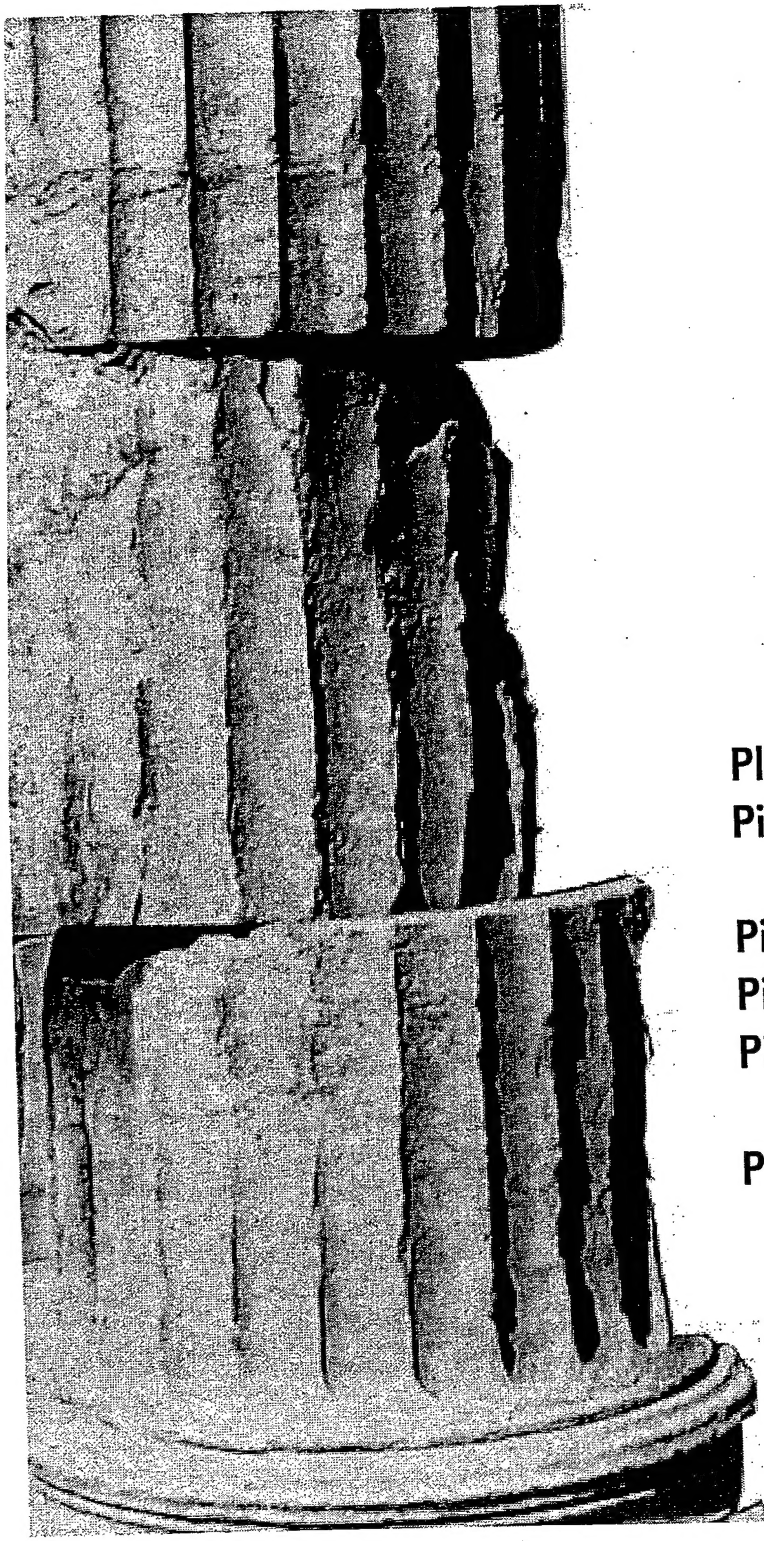

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Plenary Presentations

Pillar I	Naval Minecountermeasures (Operations) Application
Pillar II	Land Countermine (Operations) Application
Pillar III	Humanitarian Deminng (Operations) Application
Pillar IV	Unexploded Ordnance (including Improvised Explosive Devices) Application
Pillar V	Emerging Technology - Application or platform not specified

Ocean Color Satellite Derived Products in Support of Diver and Special Forces Operations during OPERATION IRAQI FREEDOM

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As missions for Explosive Ordinance Disposal (EOD) units and Special Operations Forces (SOF) move closer into coastal and even "riverine" areas, there is an increased requirement for information on water clarity. This water clarity is important from the standpoint of detecting mines and minelike objects (MLO) on the bottom, in the water column, or attached to the hull of a vessel. It is also important for insersion of an EOD or SOF divers into harbors and hostile areas undetected for demining operations. In addition, as missions move at a more demanding pace, environmental intelligence is critical in determining when and where operations are most likely to be successful. Environmenatl information is now demanded on the order of minutes to hours and not days to weeks. The reality of dealing with variable environmental conditions was no where more apparent than during OPERATION IRAQI FREEDOM (OIF). During OIF there were several missions that relied on the timely delivery of water clarity information. Here we present how ocean color imagery was utilized to support EOD and SOF operations during OIF and how algorithms developed within one week were used for active operations. We also show the integration of current data into the products that allowed the warfighter to evaluate several key environmental factors.

There has been an emergence of high and low spatial and spectral resolution satellites that can provide information to the warfighter. For marine applications the primary ocean color satellites are the Seaviewing Wide Field-of-view Sensor (SeaWiFS), and the Moderate Resolution Imaging Spectroradiometer (MODIS) AQUA and TERRA satellites. The normal resolution of these satellites is 1 Km although the MODIS satellites have 2 bands at 500 meter resolution and 2 at 250 m resolution used for atmospheric corrections. The advantage of these three satellites is that their orbits allow up to three looks at a region each day (one morning, one near mid-day (SeaWiFS), and one in the afternoon). Because of the potential information these ocean-color satellites can provide, the Navy procured license agreements to receive the daily SeaWiFS, AQUA, and TERRA MODIS imagery at key regional centers. This was to provide for local coverage and reach-back (to NAVOCEANO) capabilities. At NRLSSC and NAVOCEANO an Automated Processing System (APS), developed by NRLSSC, is used to rapidly ingest the data, update calibration coefficients, or input new alogrithms in a timely manner. Prior to OIF, image processing to proucts took about 1-2 days due to the data transfer delay and the lack of an immediate demand for optical products. During this time ocean color data was primarily used as a general "planning" tool indicating the "water clarity" that one was likely to encounter in an area.

Advancement in deriving optical properties from ocean color data in coastal regions is the key development that has lead to the more operational use of "visibility" products. Most satellites do not have the sensitivity to handle ocean, coastal, and land applications. In addition, calibration and validation of the radiometric values at the Top of the Atmosphere (TOA) are vital for most retrieval of water optical properties. Since over 90% of the TOA is

from atmospheric contributions, this poses a challenge in the obtaining calibrated radiances required for retrieval of total absorption (a(_)) and its components such as colored dissolved material and phytoplankton, particulate backscattering (b_b(_)) and the diffuse attenuation coefficient (K_d). These are the normal properties derived from ocean color. However diver visibility algorithms require absorption and total attenuation (*c*) in the "green" region of the spectrum which is the most penetrating waveband in turbid waters and is where the eye is highly sensitive.

Historically a diver visibility derived from contrast transmittance theory extended from atmospheric application has been used (Duntley 1960). The common formula for diver visibility has been $4/(c+K_d\cos(\_))$, where _ is the viewing angle, which reduces to $4/c$ for horizontal diver visibility. This equation was derived for sunny conditions, a flat sea surface, and for a black target. From a remote sensing perspective, while K_d can be derived from ocean color, *c* is not directly obtainable. To produce a 1 Km resolution diver visibility product, NRLSSC has used a ratio of 0.017 for b_b/b, that has been obtained from experimental work in the turbid Gulf of Mexico, and satellite derived absorption and backscattering.

The coefficient of "4" in the above equation is only an approximation based on the ability of the human eye to detect changes in contrast. This number varies from about 3.5 to >6. In studies with a black disk in coastal waters Davies-Colley (1988) found an average value for horizonatal visibility of about 4.8 for many water types. Similarly, recent work using Navy reserve divers observing black spheres in coastal waters of the USA resulted in average values that were within 15% of that reported by Davies-Colley. Research underway by Dr. Zaneveld also supports 4.8 for horizontal visibility). Therefore we use 4.8 as the coefficient in underwater visibility calculations.

In normal open ocean color imagery most usable bands are in the visible part of the spectrum (400-700 nm) and have a resolution of 1 Km, near infrared (NIR) channels are present but are reserved to perform atmospheric corrections (usally two 743-753 & 862-877 for MODIS Terra). The use of NIR bands for atmospheric correction in the ocean is important since the open ocean will appear "black" and is used as a "dark pixel" correction for atmospheric contributions. However as one moves into the turbid coastal regions with high sediment load, this assumption can be invalid. Consequently, there can be removal of radiance that is actually 'not' the atmospheric component and can result in negative radiances in the near-shore environments. This can be a problem for areas such as those present in the northern Persian Gulf or areas of high riverine discharge. In order to compensate for this effect NRLSSC uses a coupled ocean-atmosheric iterative model. This model determines the optimum solution for the separation of water properties and atmospheric contributions to the total radiance at the senor. This iterative algorithm approach helps correct NIR channels for contributions due to suspended material and improves optical property retrievals.

Pre-OIF efforts-

Before OIF, NRLSSC processed daily images of SeaWiFS, and MODIS AQUA and TERRA for the entire Persian Gulf at a 1 Km resolution. The APS produced horizontal visibility ($4.8/c$), K_d(532 nm), absorption of phytoplankton and dissolved organic matter, chlorophyll, and backscattering. These properties were placed on an unclassified website together with other ocean color imagery properties. Messages were sent via SIPRNET to METOC officers stating that imagery and water color properties of the Persian Gulf area were available on the unclassified website. Image products were posted for the entire Persian Gulf as well as subareas including the Straits of Hormuz, Qatar, Central Persian Gulf, and Kuwait

(Northern area). This was a "come and get it" approach and it was up to the user to browse the imagery and select which properties fit his needs.

There were three problems that were pointed out by those attempting to use the website: 1) there was too much information and the uniformed user could not identify critical information, 2) the large dynamic range of optical properties throughout the area caused features in coastal areas to be masked, and 3) the selected areas and the resolution of the products did not address the problem at hand for EOD operations. This feedback directed NRLSSC to concentrate on the northern Persian Gulf. In addition products of 1-2 days were deemed "too old" and not timely enough for operations. To address these points a "man-in-the-loop" method was implemented so that fleet users were not required to search the database. Support personnel would manually quality control an image and make a judgement on the "accuracy" and interpret oceanographic properties. A "best product" was put on a special secure website devoted to fleet users at NRLSSC. The imagery selected was a "best pixel" composite designed to give the customer a "best representation" without interpolation necessary due to cloud contamination.

OIF Operations Commence

This revised website had limited products (1 Km diver visibility) plus a 250 m resolution true color image and was sent to fleet users within the Persian Gulf area. Feedback was quick on the product. Commander Cruiser Destroyer Group 1 (CCDG1) on the aircraft arrier USS Abraham Lincoln indicated they liked the visibility product, but were more interested in the details seen in the 250 m true color image. As apparent in figures 1 and 2 there was more detail in the 250 m true color image than was being achieved in the 1 Km products. particularly near Kuwait. At this time interest had shifted to the Khawr Abd Allah (KAA) waterway (Figure 1, right-hand side). In this region the 1 Km SeaWiFS products did not have the detail desired. Communications with CCDG1 indicated that bottom hull searches and mine clearance operations would like to know areas where a 20% change in visibility was present. The poor visibility in the KAA area made knowing regions with a relative increase in visibility important environmental intelligence. The challenge presented was a request for diver visibility products using the higher resolution imagery (i.e. "can't you make diver visibility products at the 250 m resolution?"), and secondly there was a request to move even closer to the coast and up the KAA waterway towards Umm Qasr. In addition, the time delay for product dissemination was requested at the "hour level" for operations.

To extend algorithms as close to land as operationally required was well beyond any previous use of MODIS imagery in a water application scenario. There were several difficulties in using the 250 m imagery for a diver visibility product. While the 1 Km resolution ocean color imagery has bands for deriving optical properties of the water, there are no such bands at the 250 m resolution. The 250 m bands are in the red (channel 1; 620-670 nm) and NIR (channel 2; 841-876 nm) parts of the spectrum. These were normally atmospheric correction bands! The issue was to derive a visibility product when there was no algorithm for diver visibility, absorption, or any other ocean optical property using these channels. The normal atmospheric correction techniques could not be used and any derived product would need to be wavelength corrected from the red into the green waveband. Since water absorbs strongly in the red most "off-shore ocean waters" will appear black. However, for this specific customer, scientific accuracy over the entire area could be sacrificed to give higher spatial information critical for on-scene decisons at smaller spatial scales.

Since the available bands for MODIS 250 m and those for the AVHRR satellite are similar, an algorithm developed by Gould and Arnone (1997) for '*c*(660 nm)' for AVHRR was used as a starting point. This algorithm relates the remote sensing reflectance at 660 nm to *c*(660):

$$c(660\text{ nm}) = 1028.7\, Rsr(660\text{ nm})^{1.282}$$

where the 1028.7 is a scaling constant and *Rsr*(660 nm) is the total remote sensing reflectance. For our product the relationship between *c*(660 nm) and *c*(532 nm) was adjusted using a factor of 1.1 following field measurements and work of Barnard (1998) and Zaneveld and Pegau (2003). The diver visibility was then be calculated using the 4.8/*c*(532) algorithm.

In order obtain the *Rsr* (660 nm), however, an atmospheric correction was required with only the two MODIS 250 m bands. Channel 2 (841-876 nm) was used as a 'coarse' correction with radiance offshore treated as a "dark pixel" and then used as a simple dark pixel subtraction from channel one. But this method does not account for water reflectivity differences as a function of wavelength nor does it include significant parts of the Rayleigh correction components. In comparing offshore to onshore results it was clear that the trend was correct for the results but modification of the atmospheric correction was needed.

To provide a more accurate diver visibility product, the more stable and well calibrated SeaWiFS sensor (1 Km resolution) was used. After implementation of the beam attenuation (*c*) algorithms to both SeaWiFS 1Km and MODIS 250 m imagery, the derived values of '*c*' were compared. Match-ups locations were selected where there was low "spatial" variance but high '*c*' values (due to the optical properties of the KAA region). The match-ups were then regressed against one another. A linear scaling factor of 0.35 was required to provide consistent values of the MODIS 250 derived *c*(532 nm) with those from SeaWiFS. This factor was required since 1) there were slight differences between the definition used by Gould and Arnone for remote sensing reflectance ["total reflectance" needed to be translated into remote sensing reflectance], and 2) the aerosol correction was undoubtedly coarse as was evident when true color images comparison were compared.

Scripts were written for APS to provide the new diver visibility image (at 250 m resolution) within three hours of delivery of the image. Rapid image receiption was aided by NOAA who provided a special "bent pipe" so NRLSSC would recieve the imagery at the same time they did. The images were geographically corrected using a pixel by pixel method to account for bowtie effects since the imagery was being pushed into very coastal applications and even into riverine operations. Adjustments in the product were made using a Normalized Difference Vegetation Index threshold for "land" interference that may effect the '*c*' calculation. Lastly there was a visual inspection of the product, then the product was put out on the SIPRNET for the customer. The secure site allowed the user to select either the higher resolution product (Figure 3) or the 1 Km resolution products depending on their application. This Diver Visibility product was produce daily within about 3 hours of receipt of the imagery. As Figure 3 demonstrates there was great variability in diver visibility within the operational area. The visibility could range from less than 2 feet to greater than 20 feet over short spatial scales. The product was used to direct diver operations for mine clearance in the area. In figure 3 it should be noted that by using the 250 m MODIS imagery, changes in visibility up into the Khor Abdullah region toward Umm Qasr were possible. This type of environmental intelligence and product was used to determine the most likely periods and areas to examine in-water structures throughout the area.

New Product Request for SOF

As the diver visibility product was more widely distributed over the SIPRNET, other operational customers requested mission specific tailored products effected by water clarity. Immediate feedback from NAVPACMETOCEN San Diego requested a tailored product for diver and operational platform vulnerability. This vulnerability product was in response to operations by Special Operation Forces ingressing into areas up toward Umm Qasr as well as hull inspection of vessels leaving the area. A product that indicated areas where there was minimal risk of detection by surface observers was desired. Since this type of product is dependent on several optical properties and environmental factors, and not just '*c*', a new product needed to be developed. The customer also requested that the product be simplified to a Go/No-Go decision tool.

Using contrast transmittance theory, Bowers (2003) developed a numerical solution for visibility of an object of any size, reflectivity, look orientation, and in-water optical properties. For the new product this numerical model was used together with specific operational parameters provided by the customer (i.e. "operating at a depth of 10 feet" into areas within the KAA). With the value of '*c*' from the MODIS 250 m results, and some constraints on the ratio of scattering to attenuation in the area, Bowers provided estimates of diver vulnerability (assuming given size and reflectance) to surface observation at local noon under calm seas. Then using the MODIS 250 m product and a Look Up Table (LUT) for various sized objects and their reflectivity the Go/No-Go decision tool was produced. The LUT was developed for a variety of conditions in order to satisfy potential operational scenarios. A complex matrix was produced and used with APS to make the vulnerability map (Figure 5). With this map and the MODIS 250 m diver visibility product, the customer could evaluate two operational questions: 1) at what distance can I see a specific sized object, and 2) can a surface observer easily see me as I transit into an area or approach a vessel? There was good feedback from the Naval Special Warfare Mission Support Center on these vulnerability products as they were briefed to SPECWARGRU 2. With the comments recieved, these products were supplied daily as part of the SIPRNET web page.

NRLSSC also provided more products than just the visibility. These products together with the visibility product were "value-added" when evaluated in conjunction with the 250 m MODIS product. A tidal current model (PC-tides, Figure 6) and a high resolution Advanced Circulation model (ADCIRC) was developed and delivered as part of the support to OIF. The results of these products could be overlayed on the diver visibility product as shown in Figure 6 and 7 to provide the warfighter with both current and visibility information in the pre-opertion planning as well as time critical operations. Of particular interest was the effort in expanding the ADCIRC model. This is a 2D forecast coastal circulation model that uses high resolution bathymetry with outputted currents in less than one hour of computational time. The domain for ADCIRC focused on the KAA region of the northern Persian Gulf with the resolution in this area ranging from 1 m to about 400m. Resolution in the remainder of the northern Gulf was increased from 800 m to 1.8 km. Bathymetry for the model was derived from either the NAVOCEANO 1 minute resolution database (unclassified) or the 0.5 minute bathymetry (classified). The ADCIRC model utilized a finite element discretization method and therefore allowed the use of highly flexible unstructured grids that was important in extending the results up toward Umm Qasr (Figure 7). The size of the mesh and the resolution afforded in this application were never before utilized for Navy operational products related to 2D ocean circulation forecasts of depth-averaged currents and water level. A 3D model was also constructed to provide current profiles at points or transects as well as

surface and bottom layer currents. Forcing for the OIF support was derived from tides both offshore and internal to the domain. Offshore tidal forcing was taken from a larger ADCIRC domain of the entire Persian Gulf and could include wind and river forcing. The output was graphical hourly products over a 48-hr forecast period. Products included maps of water level (including the wetting/drying of tidal flats), current direction over magnitude at various depths (including the surface), time series at known data stations, and red-yellow-green decision aid maps of the maximum tidal current magnitudes during 12 hour periods (tidal currents > 3 knots = red, no go; tidal currents 1-3 knots = yellow, caution; tidal currents < 1 knot = green, go. Together with the visibility products, these offered much information for the warfigher.

While many physical tidal current models have some validation data, the validity of the optical products for the KAA product was more questionable. Within the Persian Gulf collecting hydrographic data near the time of hostilities was the USN *Dextrous*. Using a BattleSpace Profiler equipped with a '$c(532)$' meter, measurements throughout the region provided validation for the "1 Km" SeaWiFS and MODIS products (left upper panel Figure 8). At the time of delivery (less than one week after its request), there was no validation of the 250 m MODIS product. In Figure 8, the region of the operations (indicated by the box in the upper left of the Persian Gulf image) was outside the domain of any data. However, to assist in future use, on-scene survey groups and EOD/SOF units carried instruments into the area that provided some validation data (Figure 8, lower left). As indicated in this figure the 250 MODIS 'c' product performed much better than originally expected. This validation by the warfighter was greatly appreciated and provided critical information for extension of the product into other areas of denied access.

As demonstrated during OIF, METOC products from research efforts can be quickly developed and distributed to the warfighter and NAVOCEANO to support the conflict. While these are demonstrational products, on scene use and validation allowed their use as decision support tools. The response and interaction with the warfighter not only helped to provide a better product, but focused research into areas that will better aid MCM and SOF operations.

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Figure 1. Persian Gulf True Color and Study area.

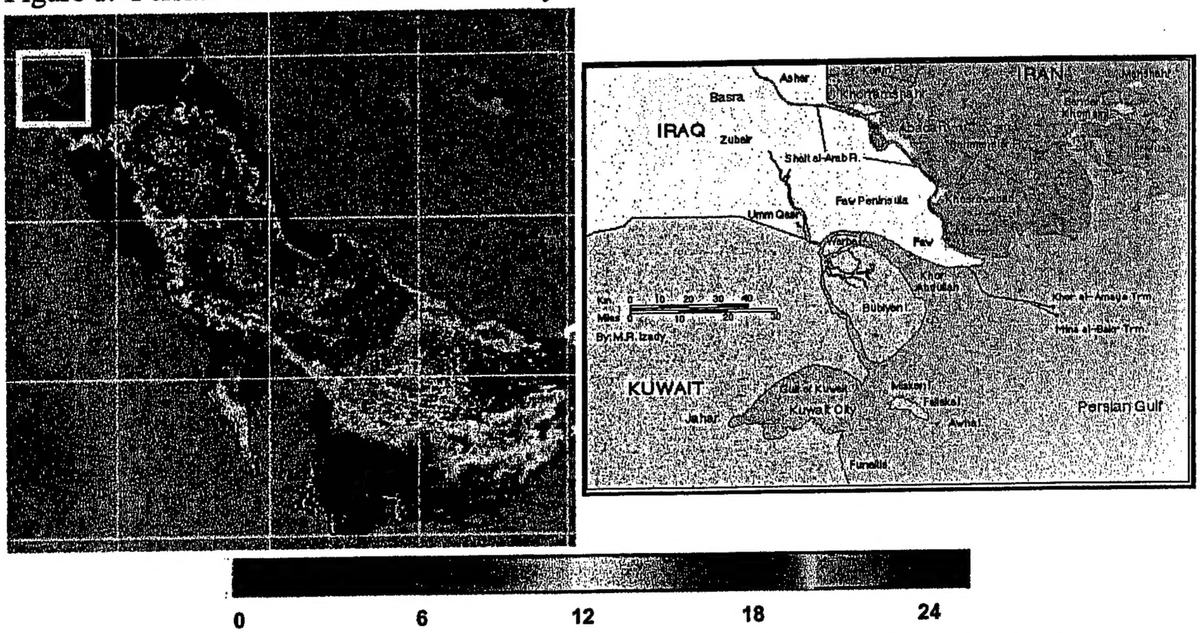

Figure 1. Initial diver visibility product (in feet) at 1 Km resolution for the entire Persian Gulf. The yellow box indicates the larger "area of interest" and the smaller inset (right) shows actual region where information was being sought. Note the problem of "little discernable details in the operational area.

Figure 2. MODIS 250 M true color

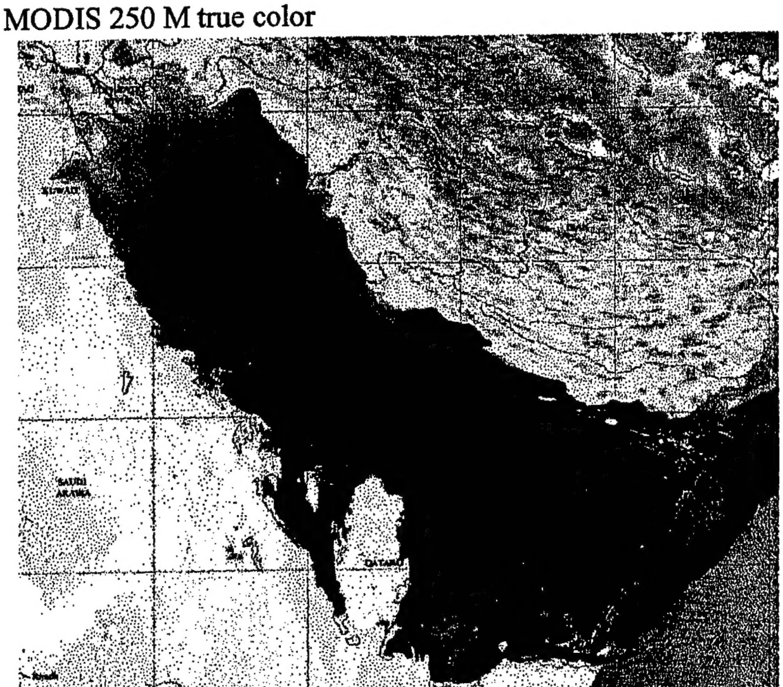

Figure 2. The 250 m MODIS True color showing features in the northern area visible in the true color that are not clearly visible in the diver visibility product.

Figure 3. High resolution diver visibility product for KAA area.

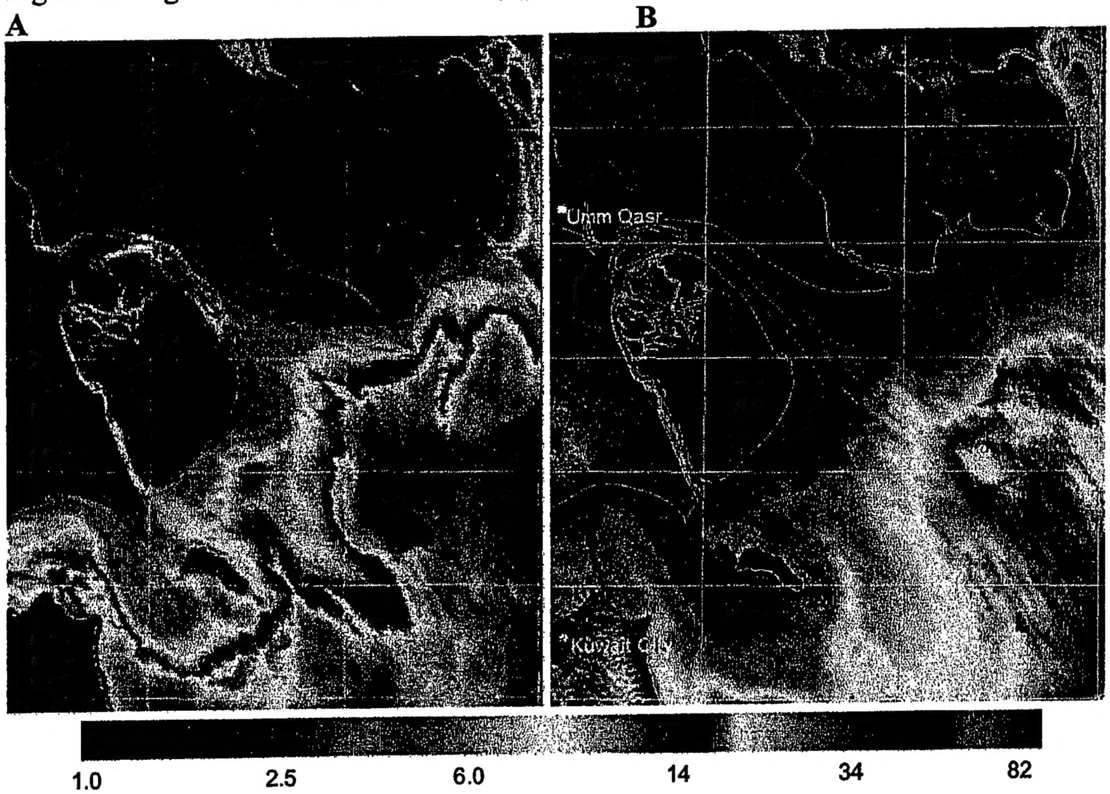

Figure 3. Diver visibility product (feet) for the KAA area using the 250 m MODIS imagery. Note clearer water up-stream on panel **A** and the more turbid water in panel **B**.

Figure 4. Example of secure webpage.

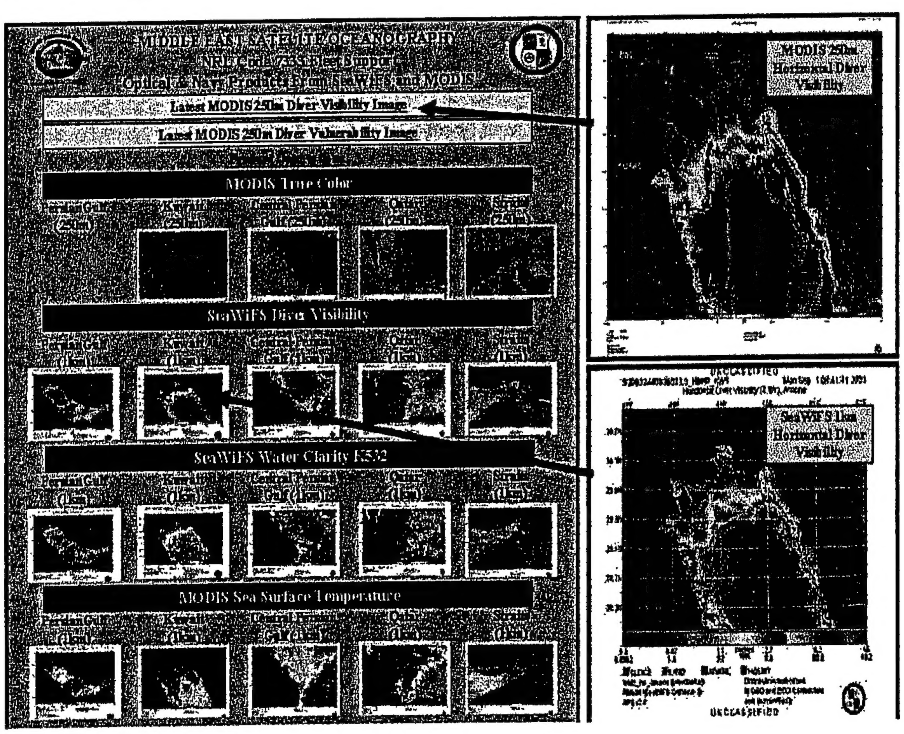

Figure 5. Mission Tool for Special Forces

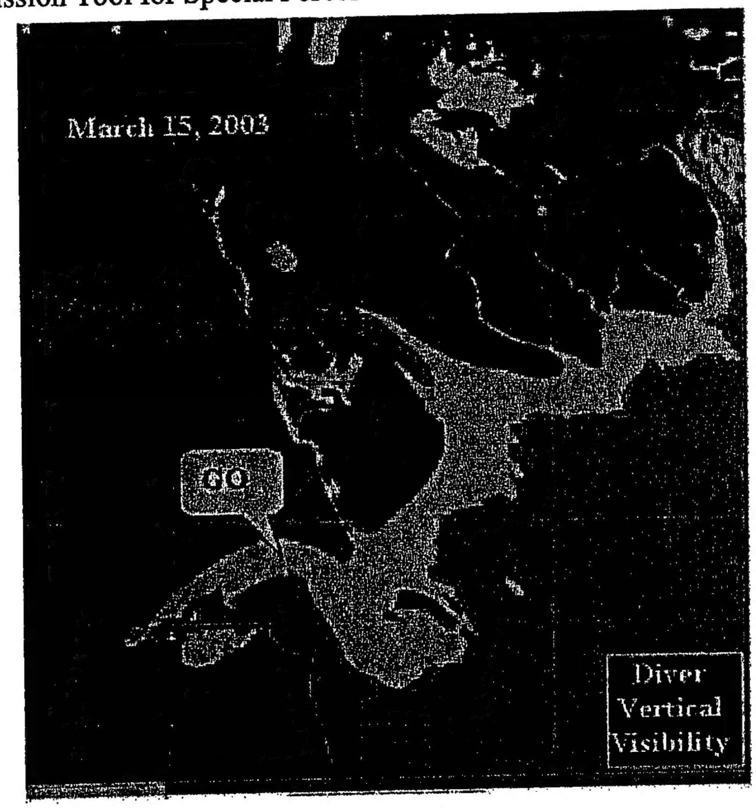

Figure 5. A Go/No-go diver vulnerability product developed for Special Forces with specific mission criteria.

Figure 6. Visibility and tidal currents

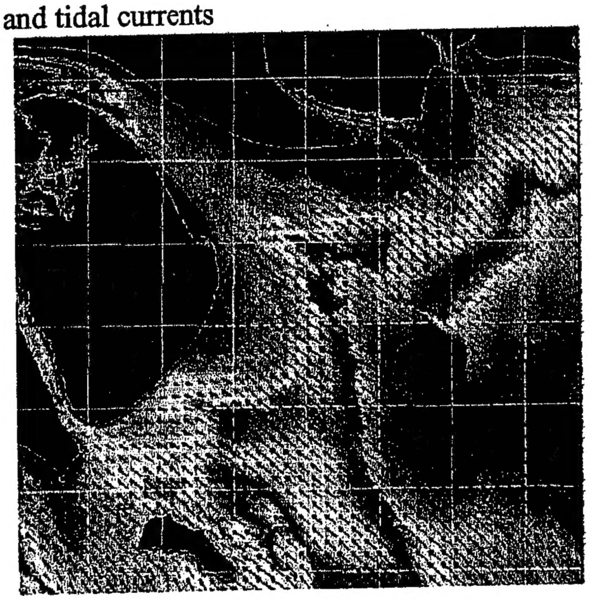

Figure 6. Modelled current field overlayed on Diver Visibility Product.

Figure 7. ADCIRC-Optics Overlay

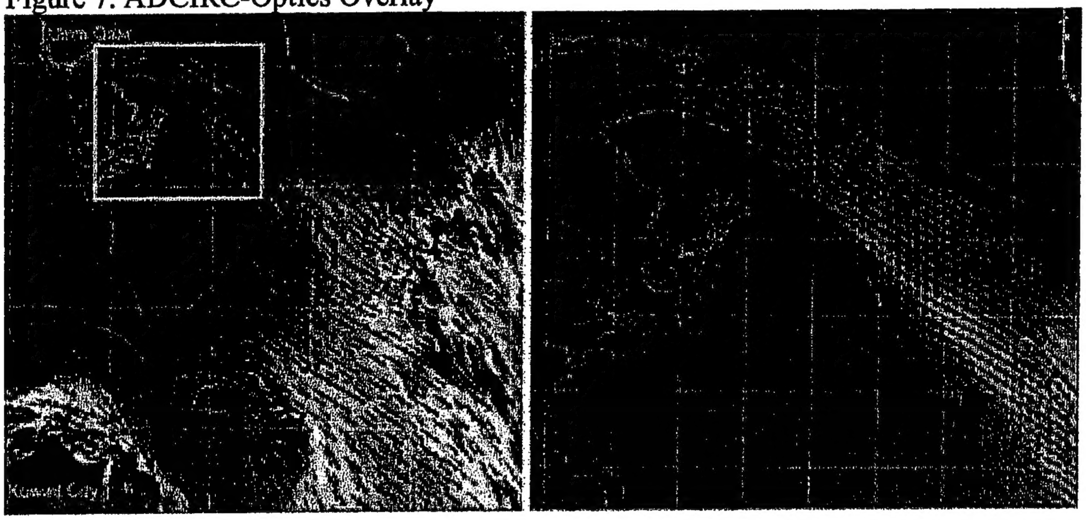

Figure 7. Advanced Circulation Model allows current field of less than 10 meter gridding and therefore was carried up-stream; however, high resolution bathymetry is required.

Figure 8. Validation of the Visibility and vulnerability products.|

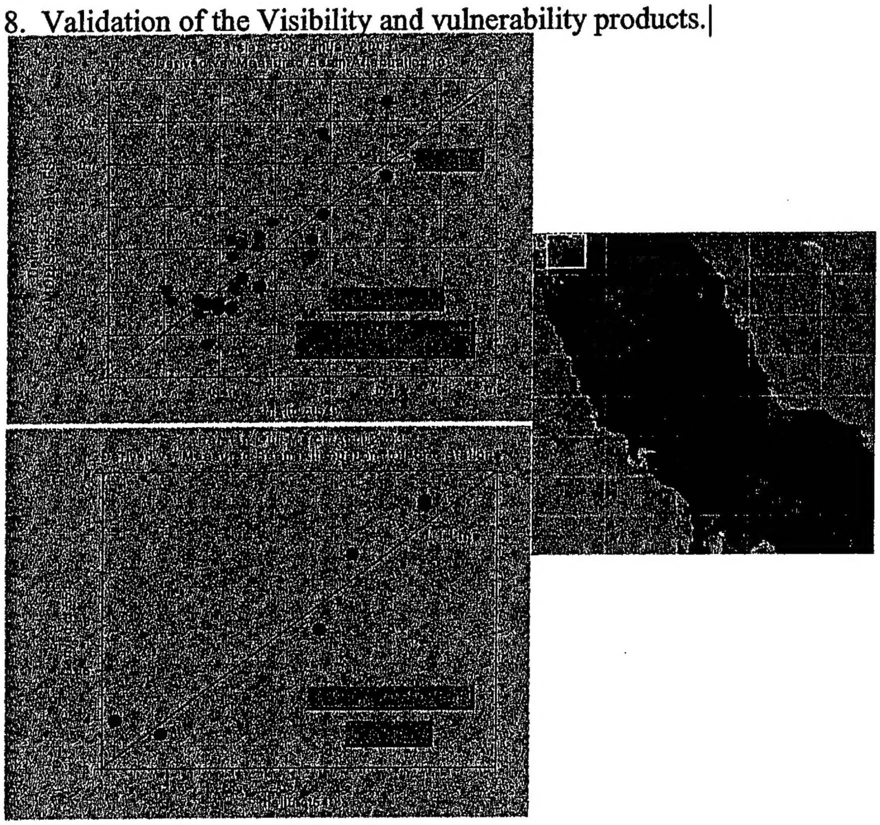

Figure 8. Calibration stations and data for the open Persian Gulf (right panel, and upper left); and results from on-scene data collection in yellow box area from operations (lower left).